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# UMENTATION PAGE

Form Approved
OMB No 0704-0188



1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
April 1993

3. REPORT TYPE AND DATES COVERED
Annual Report (12/15/91 - 10/14/92)

4. TITLE AND SUBTITLE
"Research Studies in Electromagnetically Induced Transparency"

5. FUNDING NUMBERS

6. AUTHOR(S)
S. E. Harris



7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 3 0007

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

To make an atom transparent at a given laser frequency, one applies a second laser whose frequency is equal to the difference of an otherwise empty state and the point in frequency space to which a probing laser is tuned. This type of transparency exhibits an essential nonreciprocity where, though absorption and refractive index may be negated, the nonlinear susceptibilities and coefficients for stimulated and spontaneous remain unchanged. We believe that there may be a new regime of nonlinear optics with special properties as resonances are approached.



14. SUBJECT TERMS
Electromagnetically Induced Transparency

15. NUMBER OF PAGES
15

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

Edward L. Ginzton Laboratory
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Stanford, CA 94305

# "RESEARCH STUDIES IN ELECTROMAGNETICALLY INDUCED TRANSPARENCY"

**ANNUAL TECHNICAL REPORT**

**FOR**

**THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH**

**AND**

**THE ARMY RESEARCH OFFICE**

**Contract F49620-92-J-0066**

**For the Period**

**15 December 1991 - 14 October 1992**

**Principal Investigator:**

**S. E. Harris**

**April 1993**

# I. INTRODUCTION

The overall objective of this program has been the study of the physics of extreme ultraviolet and soft x-ray lasers. Our overall objective has been to develop fixed-frequency and tunable lasers which span the 100 Å to 1000 Å spectral region. In the course of this effort we came upon the concept of lasers which might operate without population inversion. This, in turn, has led to ideas associated with electromagnetically induced transparency, and about one-half of our program is now focused in the latter area.

To make an atom transparent at a given laser frequency, one applies a second laser whose frequency is equal to the difference of an otherwise empty state and the point in frequency space to which a probing laser is tuned. This type of transparency is very different in nature than that caused by either saturation or by self-induced transparency. The critical difference is that, here, the atoms or molecules are frozen into the lower states and do not cycle or remain in the upper state. This transparency is therefore immune to both loss caused by the vacuum field and to collisions with the upper state. This type of transparency also exhibits an essential nonreciprocity which we believe to be the key to its application. We have found that, though absorption and refractive index may be negated, both the nonlinear susceptibilities and the spontaneous emission remain unchanged. We have found theoretically that there may exist what, in effect, is a new regime of nonlinear optics where the product of the nonlinear susceptibility and length remain unchanged as a resonance is approached. It should therefore be possible to increase the overall efficiency of a nonlinear process as the square of the ratio of the Doppler width to the damping rate of the intermediate

metastable state. In the Section II of this report we summarize the contributions made during this period and in Section III we list publications which acknowledge this contract. Appendix A presents the abstracts of each of these publications.

Before proceeding we note that the work described here has been, and will continue to be, jointly supported by other agencies; primarily the Office of Naval Research, the Army Research Office, and the Strategic Defense Initiative Organization.

## II. SUMMARY OF ACCOMPLISHMENTS

(1) A particularly exciting development during this contract period was the first demonstration of the use of femtosecond time scale lasers to create incoherent x-rays which extend beyond 1 MeV. We have found an energy conversion efficiency from laser energy to x-ray energy above 20 keV of about 0.3%.

(2) During this period we have completed and submitted for publication studies of the 96.9 nm laser in neutral Cs. This was the first laser to operate with its upper level above the continuum.

(3) We have underway an effort to generate very high-order harmonics using the ultra-high-power femotosecond system which was also used to produce the incoherent x-rays. As an outgrowth of this work we have noted the possibility that these high-order harmonics, to the extent that they are appropriately phased, will produce temporal structure under radiation on the order of $5 \times 10^{-17}$ sec.

(4) We have made several improvements and developments toward the realization of a new Ti:Sapphire based femtosecond laser system. A new oscillator has been constructed which produces 804 nm pulses with durations as short as 20 fs and with peak powers as high as 500 kW. Control of intracavity focusing in a high-modulation-depth, acousto-optic modulator allow the intracavity power to be maximized.

(5) During this period we have submitted for publication a study of the properties of spontaneous emission when in the presence of an electromagnetically induced transparency. We find that, because the optical depth is increased at the frequency of the transparency and the spontaneous emission is not decreased proportionately, the brightness that may be obtained is greater than that which would be predicted by the Planck blackbody formula.

(6) We have studied the dispersive properties of electromagnetically induced transparency. One result which is the basis of a forthcoming experiment is that it should be possible to obtain group velocities of about 1/500 the speed of light in a 10 cm long Pb vapor cell.

## III. PUBLICATIONS

1. K.-J. Boller, A. Imamoglu, and S. E. Harris, "Electromagnetically Induced Transparency in Sr Vapor," in *Laser Spectroscopy*, edited by M. Ducloy, E. Giacobino, and G. Camy (New Jersey, World Scientific, 1992), pp. 295-300).
2. J. D. Kmetec, C. L. Gordon III, J. J. Macklin, B. E. Lemoff, G. S. Brown, and S. E. Harris, "MeV X-Ray Generation With a Femtosecond Laser," *Phys. Rev. Lett.* **68**, 1527-1530 (March 1992).
3. S. E. Harris, J, E. Field, and A. Kasapi, "Dispersive Properties of Electromagnetically Induced Transparency," *Phys. Rev. A* **46**, R29-R32 (July 1992).
4. C. P. J. Barty, G. Y. Yin, J. E. Field, D. A. King, K. H. Hahn, J. F. Young, and S. E. Harris, "Studies of a 96.9-nm Laser in Neutral Cesium," *Phys. Rev. A* **46**, 4286-4296 (October 1992).
5. J. D. Kmetec, "Ultrafast Laser Generation of Hard X-Rays, *IEEE J. Quantum Elect.* **QE-28**, 2382-2387 (October 1992).
6. B. E. Lemoff and C. P. J. Barty, "Generation of High Peak Power 20 fs Pulses from a Regeneratively Initiated, Self-Mode-Locked Ti:Sapphire Laser, *Opt. Lett.* **17**, 1357-1369 (October 1992).
7. J. E. Field and A. Imamoglu, "The Spontaneous Emission Into an Electromagnetically-Induced Transparency," *Phys. Rev. A* (to be published).
8. J. E. Field, "Vacuum-Rabi Splitting Induced Transparency," *Phys. Rev. Lett.* (to be published).

## APPENDIX A

## ABSTRACTS OF PUBLICATIONS

# ELECTROMAGNETICALLY INDUCED TRANSPARENCY IN SR VAPOR

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**Abstract**

We report the first demonstration of a technique by which an optically thick medium may be rendered transparent. The transparency results from a destructive interference of two dressed states which are created by applying a temporally smooth coupling laser between a bound state of an atom and the upper state of the transition which is to be made transparent. The transmittance of an autoionizing (ultraviolet) transition in Sr is increased from exp(-20) without a coupling laser present to exp(-1) in the presence of a coupling laser.

## 1. Introduction

We report the results of an experiment showing how an opaque atomic transition may be rendered transparent to radiation at its resonance frequency. This is accomplished by applying an electromagnetic field between the upper state |3> of the transition and another state |2> of the atom (Fig.1). When the Rabi frequency of the coupling field exceeds the inhomogeneous width of the |1> - |2> transition, the medium becomes transparent on line center. In this work, the transmittance of an ultraviolet transition to an autoionizing state of neutral Sr is changed from exp(-20) without a coupling laser present to exp(-1) in the presence of a coupling laser.

The transparency described here is not a saturation or hole burning phenomena. As the probe laser is turned on in the presence of the coupling laser, a fraction of ground state atoms evolve to a coherent superposition state of |1> and |2>. This coherence induces an additional dipole moment on the probe transition, which cancels the primary dipole moment at the probe frequency.

# MeV X-Ray Generation with a Femtosecond Laser

J. D. Kmetec, C. L. Gordon, III, J. J. Macklin, B. E. Lemoff, G. S. Brown,[a] and S. E. Harris
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(Received 17 December 1991)

A 0.5-TW, 120-fs Ti:sapphire laser, when focused to greater than $10^{18}$ W/cm$^2$ onto a solid target, creates a plasma which emits radiation that extends beyond 1 MeV. The x-ray yield increases as the $\frac{3}{2}$ power of the incident laser energy, reaching 0.3% energy conversion to radiation above 20 keV at 40 mJ of laser energy on target. An x-ray spectral distribution of $1/E$ fits the data for most of the radiation, falling faster at higher photon energies.

PACS numbers: 52.25.Nr, 42.65.Re, 52.50.Jm

This Letter reports the generation of hard-x-ray radiation (20 keV to 1 MeV) by focusing a femtosecond laser onto a heavy metal at an intensity greater than $10^{18}$ W/cm$^2$. We use a recently developed Ti:sapphire laser system which produces a 60-mJ, 120-fs pulse at 807 nm, at a pulse repetition rate of 5 Hz [1]. We observe a maximum conversion efficiency of incident laser energy to x-ray energy of 0.3% (assuming an isotropic emission), which increases as the $\frac{3}{2}$ power of the incident laser energy. Our spectral data are well fitted by a $1/E$ distribution (x-ray yield per bandwidth) for most of the detected radiation (20 to ~200 keV), while the spectrum falls faster than $1/E$ at higher photon energies. We estimate about $10^6$ photons above 1 MeV are generated with each laser pulse.

There have recently been several experiments and studies concerned with the generation of short pulses of x rays with high power femtosecond lasers [2-6]. In these experiments the laser energy on target ranges from 2 to 250 mJ, and the highest reported x-ray energies are several keV. In contrast, we report very-hard-x-ray emission, extending 2 or 3 orders of magnitude higher in photon energy, *using only 40 mJ of laser energy.* It is likely that the radiation arises from the bremsstrahlung emission of very energetic electrons traversing the solid target. It is not clear what laser-plasma interaction mechanism produces such hot electrons on this femtosecond time scale. Hard-x-ray emission from laser-produced plasmas has been observed previously only with very large kilojoule-level laser systems, operating in the nanosecond regime [7].

To generate the x rays, we focus the laser pulse with a 5-cm focal length, diamond turned, off-axis paraboloid. At low laser power, observation of the focal region with a microscope objective and a charge-coupled-device camera indicates that 60% of the energy falls within a 3-$\mu$m-diam spot. With 40 mJ of incident energy, we anticipate the focal intensity to be near 3 EW/cm$^2$ (1 EW $= 10^{18}$ W). The focused pulse is incident on a solid tantalum target (1 mm thick) at 30° from the normal, with $p$ polarization. The round target is rotated and translated to expose a fresh surface for each shot of the laser. Surface preparation consists of only a rough polish and no experiments were conducted to determine the effect of surface preparation. A background gas of 20 Torr of air helps prevent the sputtering of target material onto the optics in the chamber. The x-ray yield was not measurably affected until about 40 Torr of air was introduced. Additionally, a 2-$\mu$m nitrocellulose pellicle is sometimes included to protect the parabolic surface.

A low intensity background pulse, which arises from amplified spontaneous emission in the amplifiers, precedes the main pulse in time. The prepulse is approximately 6 orders of magnitude less intense, and occurs for about 2 nsec before the main pulse. This is roughly 1 mJ of energy, and is sufficient to preionize the target. As the incident laser energy on target is varied, the amount of energy in the prepulse varies accordingly, such that the *peak intensity to prepulse intensity ratio is always about* $10^6$. The prepulse appears to be necessary for efficient x-ray production, although the x rays do not appear to be sensitive to the precise prepulse condition.

As shown in Fig. 1, the x rays exit from the target chamber through a 3.2-mm-thick acrylic window, located 18 cm from the plasma. This window is 60° from the target normal (opposite the laser beam), and in the same horizontal plane of the laser beam. An aperture is used near the source to collimate the x-ray beam. This aper-

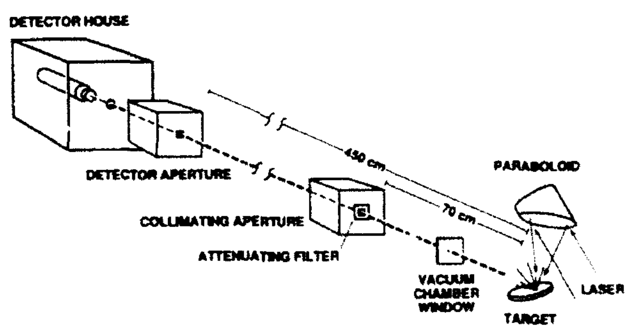


FIG. 1. Geometry of the x-ray generation and detection system. The target is rotated and translated for every shot, and the plasma occurs in a chamber containing 20 Torr of air. The tunnel apertures are constructed from 20-cm lead bricks, and the detector is completely enclosed in a 5-cm-thick wall lead brick house.

PHYSICAL REVIEW A VOLUME 46, NUMBER 1 1 JULY 1992

# Dispersive properties of electromagnetically induced transparency

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(Received 20 January 1992)

An atomic transition that has been made transparent by applying an additional electromagnetic field exhibits a rapidly varying refractive index with zero group velocity dispersion at line center. A 10-cm-long Pb vapor cell at an atom density of $7\times10^{15}$ atoms/cm$^3$ and probed on its 283-nm resonance transition has a calculated optical delay of 83 ns $[(c/V_G)=250]$.

PACS number(s): 42.50.Hz, 32.70.−n, 42.25.Bs, 42.65.An

It has recently been demonstrated that an optically thick transition may be made nearly transparent to light at its resonance frequency [1,2]. This is done by applying an electromagnetic field (Fig. 1) which dresses the upper state of the transition and thereby creates a quantum interference at a probe wavelength. The applied electromagnetic field may be another laser or a microwave or dc field. The transition may be broadened by autoionization, radiative decay, and, in certain cases, by collision.

In this Rapid Communication we calculate the dispersive properties of such a media. The real and imaginary parts of the susceptibility as functions of the probe frequency are shown in Fig. 2. Because of the absorptive interference and the symmetry of the dressed states, the probe, when tuned to the position of bare state $|3\rangle$, experiences a linear rapidly varying refractive index with very slow group velocity and zero group-velocity dispersion. This slow group velocity is the result of the slope and not of the magnitude of the refractive index, which remains nearly unity.

Tewari and Agarwal [3] and Harris, Field, and Imamoglu [4] have noted that the dispersive properties of a macroscopic medium may be modified by a strong (dressing) electromagnetic field. In related work, Scully [5] has noted the possibility of using coherence to allow an increased refractive index. The basic phenomenon which creates this transparency is termed as population trapping and has been studied extensively [6–9].

We work with the probe envelope quantities $E(t)$ and $P(t)$ with Fourier transforms $E(\omega)$ and $P(\omega)$. We take the probe to have a center frequency $\omega_0$, expand the susceptibility of the dressed atom to third order about this value, and Fourier transform. With $P(\omega-\omega_0)\equiv\epsilon_0\chi(\omega-\omega_0)E(\omega-\omega_0)$

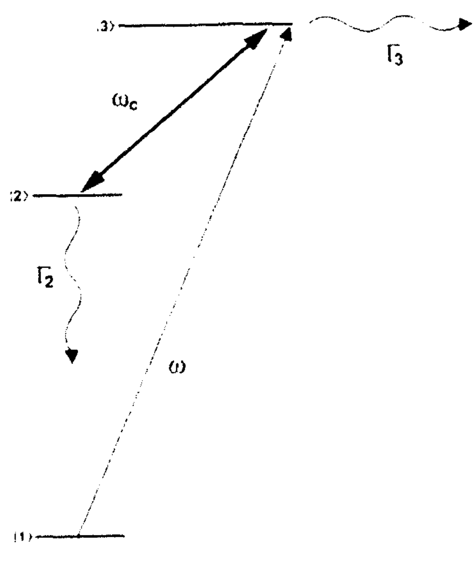


FIG. 1. Energy-level diagram for the transparency process. When a strong field of frequency $\omega_c$ is tuned to line center of the $|2\rangle\to|3\rangle$ transition, where state $|2\rangle$ is metastable, the medium becomes transparent to a field of frequency $\omega$ tuned to line center of the $|1\rangle\to|3\rangle$ transition.

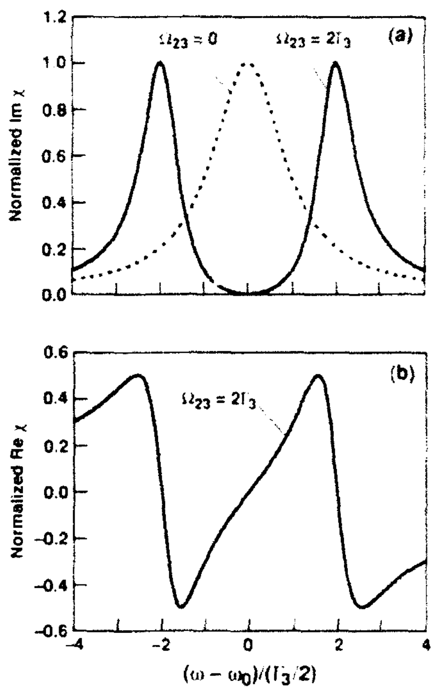


FIG. 2. (a) Imaginary and (b) real parts of the susceptibility of a probe frequency $\omega$ in the presence of a strong-coupling field $\omega_c$. The dotted curve of (a) is the imaginary part of the susceptibility in the absence of the coupling field. Normalization is to the peak value of the imaginary part of the susceptibility.

 

PHYSICAL REVIEW A VOLUME 46, NUMBER 7 1 OCTOBER 1992

# Studies of a 96.9-nm laser in neutral cesium

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(Received 4 May 1992)

Investigations of a 96.9-nm laser in neutral cesium are described. Theoretical and experimental evidence is presented for the laser level designation and pumping mechanism. Measurements of the laser output are given, including saturated pulse energy, temporal profile, spatial profile, transition wavelength, gain cross section, and the variation of small signal gain with operating parameters. Comparisons of the temporal and spatial behavior of the 96.9-nm laser emission with respect to resonance line emission from ionic Cs are also presented.

PACS number(s): 42.55.Vc, 32.80.Dz, 42.55.Lt, 42.65.Re

## I. INTRODUCTION

In 1988, gain and saturation of an extreme ultraviolet (XUV) laser at 96.9 nm in Cs vapor was reported [1]. This laser exhibited an extrapolated small signal gain of exp(83) and required less than 3 J of infrared pump energy. To the authors' knowledge, prior to this experiment, no conclusive evidence of Cs emission at 96.9 nm had been presented in the literature, nor did any theoretical supposition inferring gain at this wavelength exist. Subsequent spectroscopic evidence and atomic-physics calculations intimated that the upper laser level was embedded within the continuum of the first ion. Core-excited levels that are embedded within a continuum usually autoionize rapidly, making the accumulation of population difficult. But this need not be the case; work by Spong *et al.* [2,3] and Harris and Young [4] has shown, for example, that there are many levels in neutral Rb that have autoionization lifetimes exceeding 10 ps and several that exceed 100 ps. Such long lifetimes can result either from angular momentum and spin selection rules that, to first order, prohibit autoionization, or from fortuitous radial matrix-element cancellations. The possibility of using such levels to make extreme ultraviolet and soft-x-ray lasers has been noted by several workers [5–7]. The existence of inversion from an upper level embedded within a continuum has been inferred from fluorescence-intensity measurements by Silfvast and Wood [8].

Unlike previous laser-produced, plasma-excited, short-wavelength lasers [9,10], it was also deduced that this laser system was not directly pumped via photoionization, but was instead excited by hot electrons, which were the by-product of partial photoionization of the Cs vapor. While gain via this method had not been previously reported, the concept of photoelectron pumping was not without precedent. Wang and co-workers [11,12] used laser-produced-plasma soft x rays to create large densities of electrons in a Li and Ne mixture and consequently achieved populations of core-excited Li metastable states in excess of $10^{14}$ cm$^{-3}$. Electron excitation current densities created by this method can be on the order of $10^6$ A/cm$^2$, much larger than conventional discharge technology. Recently, this pumping mechanism has been exploited to produce a saturated output at 116 nm in $H_2$ [13].

It should be noted that, since emission at 96.9 nm in Cs had not been reported in the literature, special attention was given to other possible origins of the laser emission, including transitions in higher ion stages of Cs. The relatively well-known spectroscopy [14–17] of Cs II and Cs III yields no transition at 96.9 nm. However, the wavelength of the Cs IV analog to the now well-studied 108.9-nm Xe III Auger laser [9,18–20] is not known and was considered as a possible source of the 96.9-nm emission. Clearly, a relatively large fraction of neutral Cs is ionized early in the pump pulse and thus could be photopumped by a latter portion of the pulse. The experimental and spectroscopic evidence presented here, however, does not support this hypothesis.

In this paper a summary of our theoretical and experimental investigations of the 96.9-nm Cs laser system is presented. Studies of the spectroscopy and atomic physics of neutral Cs illuminate several unique characteristics of the laser system. Experiments investigated the origin of the laser emission, the nature of the pumping mechanism, and the characteristics of the laser output. These experiments included measurements of the pulse energy, gain cross section, temporal and spatial profile, wavelength, and the variation of the small signal gain with respect to Cs pressure, pump energy, pump duration, and degree of traveling-wave excitation. In addition, comparisons of the temporal and spatial behavior of the 96.9-nm emission with respect to line emission from ionic Cs were conducted.

## II. NEUTRAL Cs SPECTROSCOPY AND ATOMIC PHYSICS

From accurate measurement of the wavelength of the transition, reviews of published spectroscopy, and a series of atomic-physics calculations, much can be inferred about the neutral Cs XUV laser system. An energy-level diagram of the Cs 96.9-nm laser system is shown in Fig. 1. The 117 702 cm$^{-1}$ energy of the upper level has been measured by vacuum ultraviolet (VUV) absorption spec-

 

# Ultrafast Laser Generation of Hard X-Rays

J. D. Kmetec

*Invited Paper*

*Abstract*—**We have demonstrated efficient generation of X-rays above 20 keV when the tight focus of a 60 mJ, 120 fs laser is incident on a solid. We estimate 0.3% of the laser energy is converted to X-rays between 20 and 1000 keV when the target is solid tantalum. At least $10^6$ photons above 1 MeV are generated with each shot. The X-ray yield is proportional to the *Z* of the target, and scales as the 3/2 power of the incident laser energy.**

LASER-PRODUCED plasmas are well known sources of soft X-ray radiation [1]–[3]. The output of a pulsed laser system, when focused onto a solid medium, can produce a hot, dense plasma which then efficiently radiates. Typically, most of the radiation is observed in the 10–1000 eV range (1000–10 Å), and laser energy conversion efficiency can be as high as 80% [3]. Large laser systems can produce plasmas which radiate into the kilovolt region, and the largest $CO_2$ kilojoule laser systems have been able to produce diagnostic X-rays (50–150 keV) and harder [4], [5] with a conversion efficiency near 0.5% [4]. As these lasers require substantial resources and only produce a limited number of pulses per day, their use as X-ray sources has been minimal.

We have focused the output of a 60 mJ, 120 fs Ti:sapphire laser system [6] to greater than $10^{18}$ W/cm$^2$ onto a solid target. The resulting plasma generates large amounts of X-ray radiation, which has been measured with calibrated NaI detectors. Approximately 0.3% of the incident laser energy (40 mJ) is converted to X-rays between 20 keV and 1 MeV when a heavy metal such as tantalum is the target. Since the laser system operates reliably at a 5 Hz repetition rate, an average X-ray power of 0.5 mW is produced. This constitutes a significant extension of available pulsed hard X-ray sources.

Research in femtosecond laser-proudced-plasmas has concentrated on the production of soft X-rays in the 10–1000 eV range [7]–[11], and in several cases broadband and spectral line emission have been measured above 1 keV [12]–[14]. The X-ray spectrum discussed in this paper is between 20 keV and 2 MeV, which previously has been the realm of only a few large nanosecond laser systems. These X-rays are useful for traditional medical imaging, and also extend well into the domain of gamma ray emission sources. The significant features of this source of hard X-ray radiation are the potentially small source size, short pulse duration, and extreme brightness.

Generally, the time scale of the X-ray emission follows the pulse duration of the driving laser. Large $CO_2$, Nd:glass, and excimer laser systems typically produce nanosecond bursts of X-rays, and some large Nd:glass systems can produce efficient X-ray bursts in the picosecond domain [15], [16]. As high-powered femtosecond laser systems became available, questions arose whether the plasma emission would also be on a femtosecond time scale. Various calculations [17]–[19] have predicted that the soft X-ray pulse could be similarly short, since processes such as thermal conduction and adiabatic expansion of the plasma would ensure a rapid cooling. A rapid heating, provided by the laser, and a fast cooling are some necessary requirements for a femtosecond pulse of plasma X-rays. Since that time, work with several millijoules of 100 fs laser energy has shown that the X-ray emission can be less than a picosecond [7]. This measurement is limited by X-ray streak camera technology [20], and the true soft X-ray temporal evolution measurement awaits the development of an ultrafast detection method, such as correlation [21]. For reasons to be discussed, we anticipate that in this paper the X-ray source size is approximately 500 μm, and the X-ray pulse duration is subpicosecond, commensurate with the transit time broadening associated with an incoherent source of this size.

The laser system [6] used for this experiment consists of a hybridly mode-locked dye laser, pumped with a frequency-doubled CW-pumped mode-locked Nd:YAG laser. The dye oscillator utilizes LDS-798 gain dye and HITC-I saturable absorber dye, and has intracavity dispersion compensation. The 85 fs output pulses are dispersively stretched to 180 ps with an antiparallel grating pair and an inverting unity magnification telescope. These pulses are switched into a Ti:sapphire regenerative amplifier at a 5 Hz repetition rate. The regen uses 55 mJ of a frequency-doubled *Q*-switched Nd:YAG laser (Continuum NY-682) to provide nine orders of magnitude of gain, resulting in an output pulse of 8 mJ. This output is subsequently amplified in a triple-pass power amplifier to produce 110 mJ, 180 ps pulses. The power amp is pumped with the remaining 550 mJ available from the regenerative amplifier pump laser. This beam is expanded to a Gaussian exp (−2) intensity diameter of 25 mm, and temporally recompressed with a parallel grating pair.

Manuscript received February 18, 1992; revised May 18, 1992. This work was supported by the Air Force Office of Scientific Research and the Army Research Office.

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IEEE Log Number 9202056.

# Generation of high-peak-power 20-fs pulses from a regeneratively initiated, self-mode-locked Ti:sapphire laser

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Received June 15, 1992

We report the generation and measurement of 804-nm pulses with durations as short as 20 fs and with peak powers as high as 500 kW from a regeneratively initiated, self-mode-locked Ti:sapphire laser. Pulse duration is shown to decrease, and spectral content to increase, as intracavity power is increased. Control of intracavity focusing and a high-modulation-depth, acousto-optic modulator allow the intracavity power to be maximized. Cavity cubic phase error is minimized by correct design and placement of a group-velocity-dispersion-compensating prism pair.

Recently several groups have constructed Ti:sapphire oscillators capable of producing pulses of less than 50 fs in duration.[1-6] In this Letter we present a twofold approach to the generation of short pulses in which we minimize cubic phase error in the laser cavity by correct design and placement of intracavity prisms and increase the phase-locked spectral content of the laser pulse by systematically raising the intracavity pulse power. This approach has resulted in pulses as short as 20 fs and peak pulse powers as high as 500 kW at a 100-MHz repetition rate. Such pulses may be useful for the study of nonlinear phenomena or as high-energy seed pulses for amplification systems.

A schematic of our laser oscillator is shown in Fig. 1. The intracavity focusing mirrors, the 2-cm Ti:sapphire rod, and the rod housing are taken from a commercial cw Ti:sapphire laser (Spectra-Physics Model 3900). The position of one focusing mirror is micrometer controlled and allows for the adjustment of overall intracavity focusing without affecting cavity alignment or dispersion.

Self-mode-locking is initiated by a regeneratively driven[7,8] intracavity acousto-optic modulator (AOM) (Brimrose Model FSML-4.4-2-C*). At 5-W rf power, this AOM has a minimum modulation depth of 20% over a continuous range of modulation frequencies from 70 to 110 MHz. This high nonresonant modulation depth not only provides the initial perturbation required for self-mode-locking to begin but also helps to suppress concurrent cw modes that develop under highest-power operation. This latter effect is confirmed by the observation that, when the AOM is turned off, one or more narrow lines appear over the otherwise unchanged pulse spectrum.

Another important cavity consideration is the design and placement of group-velocity-dispersion (GVD)-compensating prisms. For pulses shorter than ~50 fs, cubic phase error ($d^3\phi/d\omega^3$) in the laser cavity can limit the pulse duration.[3,4,6] The dispersion of a prism pair is determined by the composition, apex angle, angle of incidence, intraprism path length, and interprism separation. We use a dispersive ray-tracing analysis to calculate exactly the effects of all these parameters on all orders of dispersion. Given Brewster-angled prisms and a desired amount of negative GVD, the interprism separation is determined by the prism composition and the intraprism path length.

In Fig. 2 we show the round-trip cubic phase error, at 800 nm, as a function of prism composition and single-pass intraprism path length for a net zero-GVD cavity consisting of a 2-cm sapphire rod and a prism pair. The results for finite values of GVD are qualitatively the same. From Fig. 2 we see that cavity cubic phase error is minimized for most of the materials shown when the beam passes as closely as possible to the prism apices. This effect is especially pronounced in SF10. Experimentally, with SF10 prisms (no AOM in the cavity, prism separation of 22 cm, intraprism path length ≤ 4 mm), we have been able to generate pulses as short as 26 fs. For BeO (Ref. 9) prisms, there is actually a finite intraprism path length that simultaneously nulls GVD and cubic phase. Optical-quality BeO, however, is not a commercially available material. The next best choice of material would be fused silica, but that would require an interprism separation of 143 cm (with the AOM in the cavity). We use LaK31 prisms, the required separation being only 50 cm. For LaK31, we calculate a residual cubic phase error

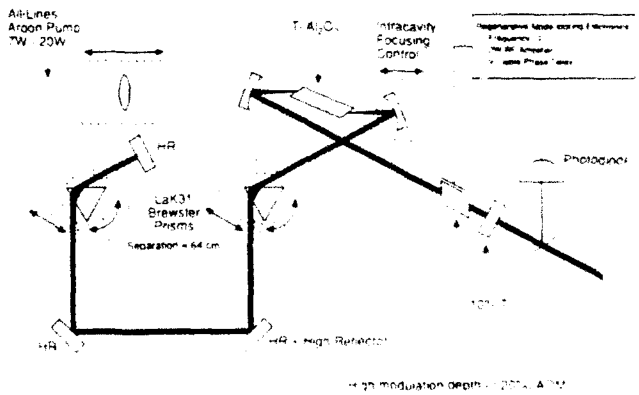


Fig. 1. Schematic of the Ti:sapphire oscillator

0146-9592/92/191367-03$5.00/0 

# The Spontaneous Emission into an Electromagnetically-Induced Transparency

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## Abstract

We investigate the spontaneous emission into an electromagnetically produced transparency of the form recently proposed. [A. Imamoğlu and S.E. Harris, *Opt. Lett.*, 1344 (1989).] We show that the achievable radiation temperature (or brightness) at the transparency is much greater than the atomic temperature.

# Vacuum-Rabi Splitting Induced Transparency

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Abstract: The vacuum Rabi splitting may be observed with population trapping techniques. The trapped population has a lifetime much greater than the natural lifetime of the atomic transition; as a result, vacuum Rabi splittings that are much smaller than the natural lifetime may be observed. A condition for lasing without inversion in this system without any externally injected coherent field or coherence is stated.